

TITLEPREPARATION AND USE OF GAMMA-BUTYROLACTONES
AS CROSS-LINKING AGENTSFIELD OF THE INVENTION

5 This invention relates to the preparation of gamma-butyrolactones and their use as cross-linking agents in various processes, including coating applications. Gamma-butyrolactones as cross-linking agents impart favorable properties to coating materials, do not pose serious health risks in commonly used coating processes, and therefore are suitable alternatives for isocyanates in coating compositions and application processes.

TECHNICAL BACKGROUND OF THE INVENTION

15 Materials commonly used for coatings, particularly those used in the automotive industry, utilize isocyanate compounds in coating formulations due to cross-linking properties of the compounds. Diisocyanate compounds react slowly at room temperature with amines and aliphatic alcohols to make polymers having urethane or urea crosslinks. Isocyanates may also cross-link with amines or alcohols during a baking step of the coating process and result in urethane or urea crosslinked polymers. Both urethanes and ureas are known to impart desirable properties in coating materials. Polymer backbones appended with hydroxyl groups or amine groups harden coating materials such as paint.

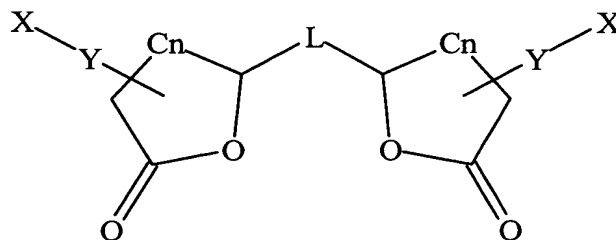
20 Isocyanates are volatile compounds. During the coating or baking step, persons working in the automotive industry, for example, are exposed to the vapors. Concern about the potential toxicity and health related effects associated with isocyanates suggests that alternatives are needed. The present invention discloses alternatives to isocyanates as cross-linking agents.

SUMMARY OF THE INVENTION

25 Disclosed in this invention is a lactone composition, as represented in structure I, wherein each n is independently 1 to 3; L is either present as a substituent having two functional groups, or is a direct bond forming a spiro-butyrolactone, or is H wherein rings of the structure are not connected, or is a radically polymerizable group wherein the rings of the structure are not connected; Y is either present independently as alkyl, alkenyl, alkynyl, aryl or a direct bond; each X is independently a substituent having a field effect, F, between -0.42 and +1.58

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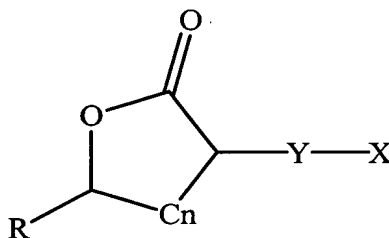
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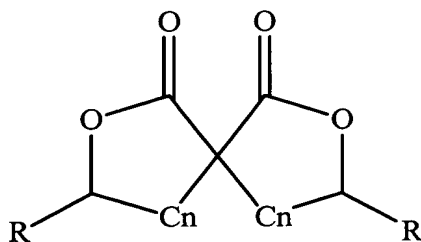
Also disclosed in this invention is a process comprising contacting
 10 lactones of structure B with an amine to form a hydroxy amide, wherein each Y is
 present independently as alkyl, alkenyl, alkynyl, aryl, or a direct bond; each X is
 independently a substituent having a field effect, F, between -0.42 and $+1.58$;
 wherein R is a branched or straight chain alkyl group of C_1 to C_{10} , or an aryl
 group; and wherein each n is independently 1 to 3.

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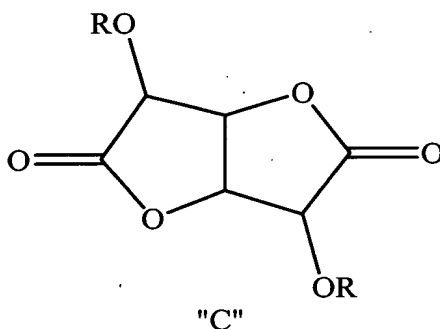
"B"

This invention also discloses a process comprising contacting a spiro-
 bislactone of structure A, wherein each $n = 1$ to 3 independently and R is a
 20 branched or straight chain alkyl group of C_1 to C_{10} , or an aryl group; with an
 amine to form a hydroxy amide.



"A"

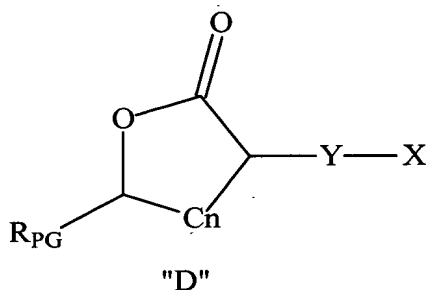
Also disclosed in a process comprising contacting a bicyclo-lactone of structure C wherein R is a branched or straight chain alkyl group of C₁ to C₁₀, an aryl group; or C(O)OE wherein E is independently alkyl or aryl, with an amine.



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Also disclosed in this invention is a process comprising contacting a polymer comprising at least one polymerized lactone monomer of structure D with an amine to form a hydroxy amide, wherein each Y is present independently as alkyl, alkenyl, alkynyl, aryl, or a direct bond; each X is independently a substituent having a field effect, F, between -0.42 and +1.58; and wherein R_{PG} is a radically polymerizable substituent group selected from the group consisting of styrene, acrylate, methacrylate, acrylamide, and methacrylamide; and wherein n is independently 1 to 3.

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Still another disclosure of this invention is a process, comprising:
(i) performing the steps of any one of the disclosed processes; and applying a product resulting from step (i) to an object surface.

Also disclosed is an article treated by a process disclosed as described above.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a plot of the relative aminolysis rates, expressed as $\log(k/k_0)$, for the substituted gamma-butyrolactones versus the F values for the functional groups as given in Hansch, et al., Chem. Rev., 1991, 91, pp. 165-195. The x axis is labeled "F". The letter "F" refers to the substituent constant that is related to the "field effect".

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Figure 2 is a plot depicting the aminolysis rate of gamma-butyrolactone..

DETAILED DESCRIPTION OF THE INVENTION

Isocyanates are used extensively in materials used as coatings. One example of isocyanate use is in the automotive industry. Isocyanates are used as cross-linking agents for coating automobiles during different manufacturing coating processes. Concern has increased over the potential health hazards associated with the use of isocyanates. This present invention discloses alternatives to coating formulations comprising isocyanates and alternatives to the use of isocyanate formulations in coating processes, including electrocoat (E-coat), original equipment manufacturing (OEM), and Refinish.

The aminolysis of gamma-butyrolactones may be described as an amide forming reaction caused by the reaction of a primary amine with a cyclic ester, or lactone, to give a hydroxyamide. Lactones do not always react with amines quickly enough for application as a cross-linking agent in some coating processes. When the aminolysis reaction proceeds too slowly, the curing of the material is time consuming. For room temperature curing, a reaction that proceeds too slowly is industrially inefficient. An increased aminolysis reaction rate at or about room temperature produces a crosslinking agent which is useful for clear coats and color coats. Such processes are used in automotive body repair shops (i.e., Refinish), for example, where baking the finish is impractical. However, for applications where baking is required, if the aminolysis reaction rate is increased too sharply, the accelerated reaction may result in an aesthetically and mechanically undesirable coating, because the prepolymer begins to crosslink in the baking process before the coating has had enough time to flow out to form a smooth surface, thus resulting in a rough surface. These problems are resolved by the present invention.

In this invention the aminolysis rate can be predicted, thereby providing alternatives to currently used processes. This invention can be tailored to the particular coating process. An adjustable aminolysis reaction rate can result in a crosslinking agent which yields a melting and flowing of the coating material to produce a smooth and evenly coated surface when such a surface is desired.

Specifically, this invention discloses compounds and processes to predictably adjust the rate of aminolysis of gamma-butyrolactones by appending a substituent having a known field effect value (F) to the alpha position of a gamma-butyrolactone before reacting the lactone with an amine. The resulting compound of the aminolysis is a gamma hydroxy amide, which can be used as the cross-linking group in a variety of coating formulations and processes. Throughout this description, reference is made to gamma-butyrolactones.

However, it should be understood that this invention is not limited to gamma-butyrolactones, but also covers delta- and epsilon-lactones, as indicated by structure I.

After many years of effort, physical organic chemists developed a number of sigma constants to apply to various aromatic and aliphatic reactions. C. G. Swain and E. C. Lupton, J. Am. Chem. Soc., 1968, 90, 4328, reanalyzed the data that was used to develop the sigma constants σ_m , σ_p , σ_p^- , σ_p^+ , σ_I , σ_R^0 and found that the sigma constants were not independent. The sigma constants contained contributions from both resonance and field contributions. It was discovered that a linear combination of two sets of new values "F" (which expresses the field-effect contribution of a functional group) and "R" (which measures the resonance contribution of the same group) satisfactorily expressed 43 sets of σ values. Each set was expressed as

$$\sigma = fF + rR$$

where "f" and "r" are weighting factors. The importance of the expression is that the electronic effects of a given substituent could be separated and expressed as only two constants. A useful set of F and R values is given in C. Hansch, et al., Chem. Rev., 1991, 91, pp. 165-195, herein incorporated by reference.

Having derived a universal set of F and R constants for substituent groups, these can then be used in a Hammett equation to examine the effect of a particular substituent on the reaction rate of a particular reaction. In general, the Hammett equation can be written as

$$\text{Log } (k/k_0) = \rho F + \rho R$$

where (k/k_0) is the relative reaction rate, ρ is rho, and F and R are the field and resonance contributions of the substituent groups. The slope of the line, called rho, is given the Greek symbol, ρ , and represents the sensitivity of the reaction to the variation of substituents. (An explanation of the use of Hammett equations can be found in J. March, "Advanced Organic Chemistry", 3rd ed., John Wiley & Sons, Inc., N.Y., 1985, pp 242-250 and references cited therein, and is herein incorporated by reference.) In order to use the Hammett equation to predict the relative reaction rates of lactones, it was first necessary to establish that the Hammett equation applies to aminolysis of lactones. For aliphatic lactone rings, only the field effect should apply since the resonance effect is absent in compounds that do not have conjugated double bonds joining the substituent with

the reaction center. In this case, the reaction center is the lactone carbonyl group. Since resonance contributions to the aminolysis reaction of a saturated lactone are absent, the Hammett equation given above can be modified to give

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$$\text{Log } (k/k_0) = \rho F$$

The relative aminolysis reaction rate for a lactone possessing a given substituent was plotted against the F value for the given substituent. If the Hammett equation applies, the resulting set of points should form a straight line that passes through the origin [0,0]. The relative reaction rate for various lactones was plotted against F and is shown in Figure 1. The resulting points were fitted to a straight line using a linear least squares equation. The resulting line has a correlation coefficient of 0.992. It was not known beforehand whether lactones would obey the Hammett equation. From this novel result, it can be concluded that the Hammett equation can be used to relate and predict the effect of an alpha substituent on the aminolysis reaction rate of a cyclic lactone. Using such a high correlation coefficient, our invention utilizes an understanding of how to substitute a lactone, having 3 to 6 members in the lactone ring, to give any reaction rate desired. One can speed up or slow down the aminolysis reaction at will by the choice of substituents.

From Figure 1 it can be seen that the relative reaction rates vary by almost five orders of magnitude. It is experimentally difficult to employ uniform reaction conditions when such large differences in relative reaction rate are found. On some of the fastest reacting lactones, the concentration of the reactants had to be reduced by half in order to determine their reaction rates. The rates were then adjusted to account for the effect of dilution. The adjustment is based on aminolysis studies performed on acyclic esters; in these studies, the reaction rate was found to obey the rate law

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$$\text{Rate } (R) = k_1 [\text{amine}]^2 [\text{ester}] + k_2 [\text{amine}] [\text{ester}]$$

(See F. M. Menger and J. H. Smith, J. Am. Chem. Soc., 1972, 94(11), 3824-3829). The dominant term in this expression is the second one since the magnitude of the rates k_1 and k_2 are approximately equal; this means that the observed reaction rate will be increased by a factor of 4.0 when the concentration of both amine and lactone are reduced by half. The rate law for lactones is similar to those for esters. The relative reaction rate can then be adjusted by the inverse of 4.0, i.e., 0.25, to compare the reaction rates of the diluted lactones with lactones that have not been diluted.

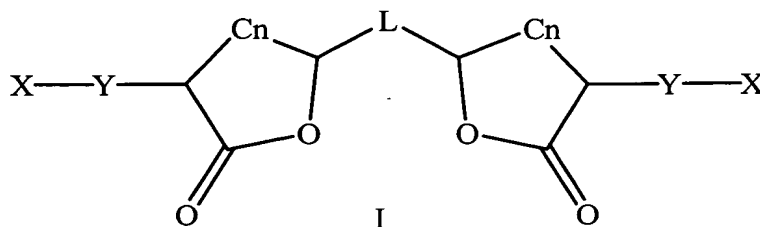
In the aminolysis of lactones, the reaction rate was not determined directly. What was determined was the half-life of the reaction, $t_{1/2}$, which is the point in time when the concentration of lactone or amine becomes equal to the concentration of hydroxyamide. For a second order reaction $t_{1/2} A = 1/(k[A])$, where $[A]$ is the concentration of lactone A and k is the reaction rate. Thus $k = 1/(t_{1/2} [A])$. Similarly, the reaction rate for the standard, k_o , is $k_o = 1/(t_{1/2} [B])$. When the half-life of lactone A is compared to the half-life of a standard lactone, B, it is seen that the ratio of reaction rates is inversely proportional to the ratio of half-lives (see C. Capellos and B.H.J. Bielski, "Kinetic Systems", Wiley-Interscience, NY, 1972, p 4).

$$(k/k_o) = (1/(t_{1/2} [A])) / (1/(t_{1/2} [B])) = t_{1/2B}/t_{1/2A}$$

These adjusted reaction rates are exemplified and depicted graphically in the plot of Figure 1. Equal quantities of N-butylamine and substituted lactone were allowed to react at room temperature (22°C) in an NMR tube. The integrated intensity of the CH_2 adjacent to the amide nitrogen in butyl amine and the CH_2 of the resulting hydroxyamide was measured by 1H NMR. The integrated intensity was plotted against time and the time when the curves crossed was taken as the half-life of the reaction, since at that time both species (amide and butylamine) were equal in concentration. Since all concentrations of reactants were kept the same, the relative rates (k/k_o) are proportional to the relative cross-over times.

The relative "F" values provide predictable information about the aminolysis reaction rate for those substituents where F equals from about -0.42 to about +1.58, which applies to more than 500 substituents. Various electron withdrawing groups, which have an F value greater than 0.03, and which are appended to the alpha position of the lactone carbonyl group give "activated" lactones. By "activated" is meant a lactone having electron withdrawing properties. Various electron withdrawing groups may be used, including -CN and -C(O)COR. Lactones having these substituents have different reaction rates. The electron withdrawing groups can be classified by their F values. Positive F values indicate electron withdrawing properties and negative F values indicate electron donating properties. H is assigned an F value of 0.03. The F value of a group is related to the half-life of the reaction of lactones with amines. For example, the adjusted half-lives of -CN, -C(O)COR and -H are about 1.25 minutes, about 88 minutes and about 165 hours, respectively.

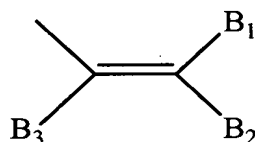
In an embodiment of this invention, the substituted gamma-butyrolactone has the structure:



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wherein each n is independently 1 to 3; L is a bifunctional compound or nothing; each Y is independently nothing, alkenyl, alkynyl, or aryl; each X is independently a substituent having a field effect, F, between -0.42 and $+1.58$; wherein when Y is nothing, then X is appended directly to the lactone ring;

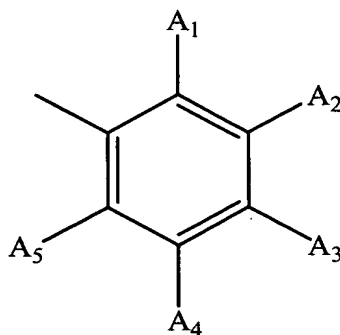
10 wherein when L is hydrogen, the lactone rings are not connected; and wherein when L is nothing, the lactones form a spiro-bis lactone (See Fig. A below). When Y is alkenyl, the alkenyl group is defined as



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wherein each B_1 to B_3 is individually a substituent group X as defined above.

When Y is phenyl, the phenyl group is defined as



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wherein A_1 to A_5 are each individually a substituent group X as defined above. When Y is an alkynyl group, it has the structure

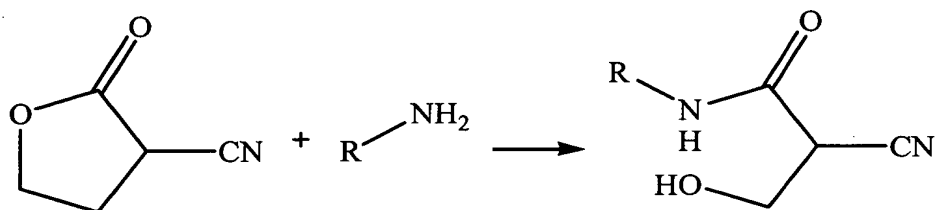


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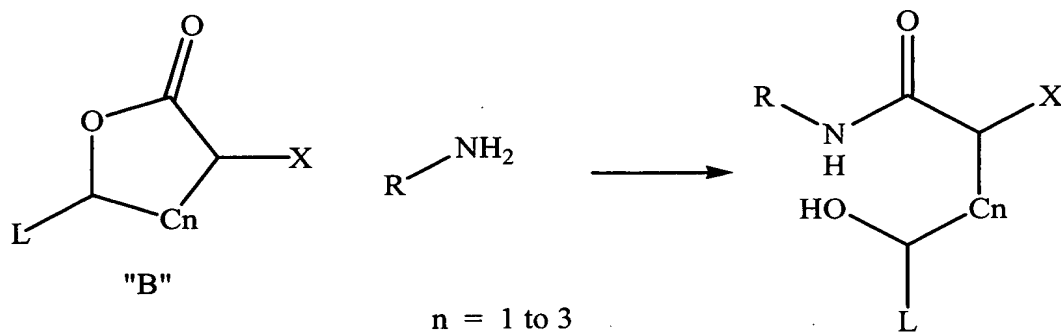
where X is as defined above.

Any primary or secondary amine with a reactive amino group is suitable for this process. Primary amines are preferred.

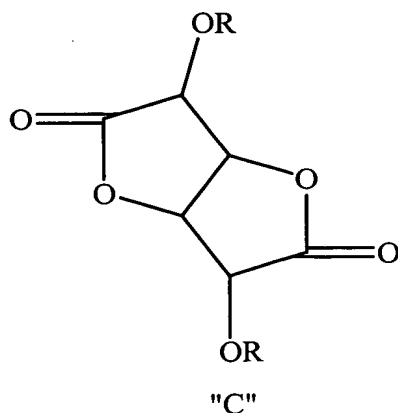
- 5 During this reaction the lactone rings opens and a gamma-hydroxy amide is formed. For example, where $-CN$ is the activating group on the lactone, the reaction can be depicted as



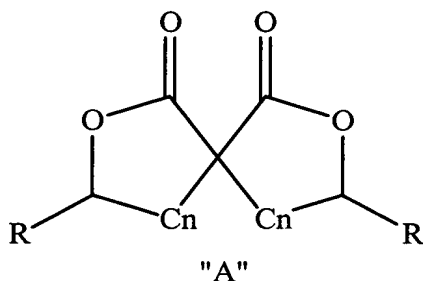
- 10 This invention discloses the use of spiro (A), substituted (B) and bicyclic (C) lactones of the following structures, as well as the use of polymers, such as acrylic polymers, containing lactone group(s) prepared from lactone monomers (D) of the structure reported below



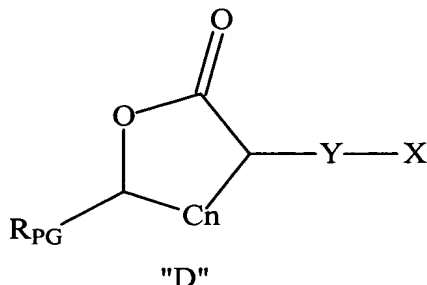
- 15 The bicyclic lactone can have a structure such as



- 20 and the spirolactone can have a structure such as



and the lactone monomer can have the structure



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for use as cross-linking agents in coating processes, wherein the linking group, C_n , is defined for when $n = 1$ to 3, preferably $n = 1$ to 2 and most preferably $n = 1$. The F values for substituent X and reaction temperatures permits customization of the reaction for the coating process by predicting the aminolysis rates of the cross-

10 linking agent. In one embodiment of this invention bis-lactone is reacted with an amine. In another embodiment of this invention a monolactone is reacted with a diamine or an aminoalcohol. The substituents which are useful to activate the lactone disclosed in this invention are functional groups having an F value from about -0.42 to about 1.58 and are provided in Table 1.

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The preferred substituents, X, are found in Table 1, identified with the numbers 2, 5, 15, 28, 30, 32, 33, 34, 35, 37, 40, 43, 45, 47, 48, 49, 58, 62, 70, 74, 75, 76, 77, 78, 80, 84, 85, 90, 93, 94, 95, 97, 98, 99, 100, 101, 102, 103, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 122, 125, 127, 128, 133, 139, 141, 142, 143, 144, 148, 150, 151, 153, 156, 160, 161, 162, 163, 165, 166, 167, 168, 169,

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The most preferred substituents, X, are found in Table 1, identified with
the numbers 2, 5, 15, 28, 32, 33, 40, 45, 49, 70, 75, 76, 78, 80, 84, 85, 90, 93, 99,
15 100, 101, 102, 103, 111, 117, 118, 119, 120, 122, 125, 127, 128, 133, 139, 141,
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379, 380, 384, 388, 395, 396, 403, 404, 405, 406, 407, 408, 409, 410, 411, 416,
417, 420, 424, 425, 433, 448, 449, 450, 453, 458, 460, 474, 475 and 512.

Temperatures of the process is not critical, a preferred temperature range
25 for ambient (Refinish) curing is about -20°C to about 120°C, more preferably
about 0°C to about 110°C, and especially preferably about 10°C to about 100°C.
Preferred temperatures for E-coat or OEM applications are not critical, a preferred
temperature being in the range of 20°C to about 250°C, more preferably about
40°C to 220°C, most preferably about 100°C to 200°C. Ratios of reactants are
30 not critical, but in order to most efficiently utilize the ingredients a molar ratio of
about 1:1 for the lactone and primary amine groups is preferred.

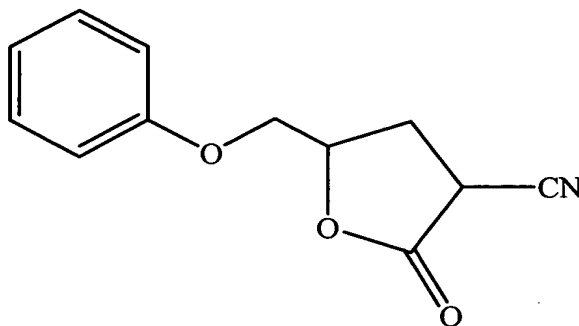
In general, all that is necessary for the reaction to occur is to bring the
reactants into contact, as in solution, or if one or both of the primary amine and
lactone are liquids, without solvent, for a period of time sufficient to carry out the
35 reaction.

Polymers that contain lactone groups are especially useful since they may
be crosslinked by multifunctional compounds that can react with lactone groups.
Multifunctional amines are particularly desirable in this respect, since upon

Synthesis of Substituted Gamma-Butyrolactones

EXAMPLE 1

Synthesis of 3-cyano-5-phenoxyethyl-gamma-butyrolactone

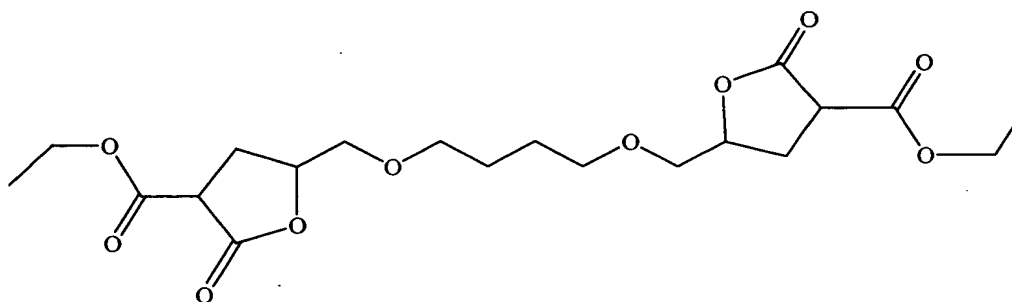


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- A 4-necked 500 ml round bottomed flask equipped with a nitrogen bubbler, reflux condenser, and stirrer was charged with 250 ml of ethanol. Over a period of 10 minutes 2.4 g of sodium hydride was added with stirring. After stirring for 10 min., a solution of 3.3 g of malononitrile in 10 ml of ethanol was added. To this mixture was added during 15 min. a solution of 7.5 g 1,2-epoxy-3-phenoxypropane from an addition funnel. The reaction mixture was refluxed for 2 hours and then allowed to stand overnight at room temperature. The solvent was removed on a rotary evaporator and the residual syrup was dissolved in 250 ml of methylene chloride and reacted with 250 ml of 1 N hydrochloric acid for 30 min. The methylene chloride layer was separated and the water layer was washed with 25 ml of methylene chloride. The methylene chloride layers were combined, washed with 200 ml of water, and dried over magnesium sulfate. The solvent was removed. The residue was dissolved in ethanol, treated with charcoal, and filtered. The filtrate gave 3.6 g of white crystals mp 125-130°C. IR (nujol) 1785.66 and 1772.54 cm^{-1} (cis and trans isomers of lactone carbonyl). ^1H NMR (acetone- d_6) 5.1 and 5.2 ppm (both m, cis and trans isomers of 5-H lactone ring).

EXAMPLE 2

Synthesis of 5,5'-[1,4-butylenebis(oxymethylene)]-bis[ethyl(tetrahydro--2-oxo)-3-furancarboxylate]



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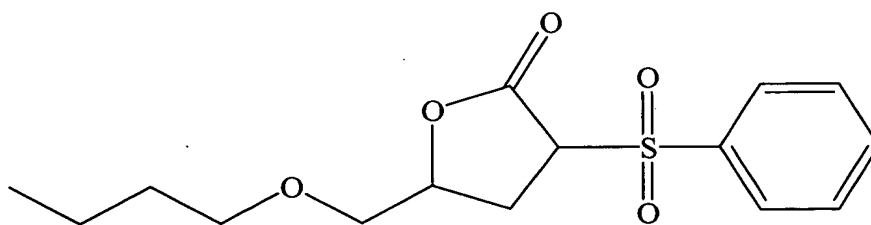
A 2 liter 4-necked round bottomed flask equipped with a mechanical stirrer, reflux condenser, nitrogen bubbler and thermocouple thermometer was charged with 600 ml ethanol and 58.08 g of sodium methoxide. Then, while stirring, 168.2 g of diethyl malonate was added followed by 101.1 g of 1,4-butanedioldiglycidyl ether. The reaction was refluxed for one hour. The reaction was neutralized with 5% hydrochloric acid and extracted four times with 250 ml of methylene chloride. The methylene chloride layers were combined and washed with 100 ml water, separated, dried over magnesium sulfate, filtered, and concentrated to give a syrup. IR (neat) 1780.64 and 1731.25 cm^{-1} (cis and trans lactone isomers). ^1H NMR (CDCl_3) 4.7 and 4.8 ppm (both m, cis and trans isomers of 5-H lactone ring).

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EXAMPLE 3

Synthesis of 3-benzenesulfonyl-5-methyleneoxybutyl-butylolactone



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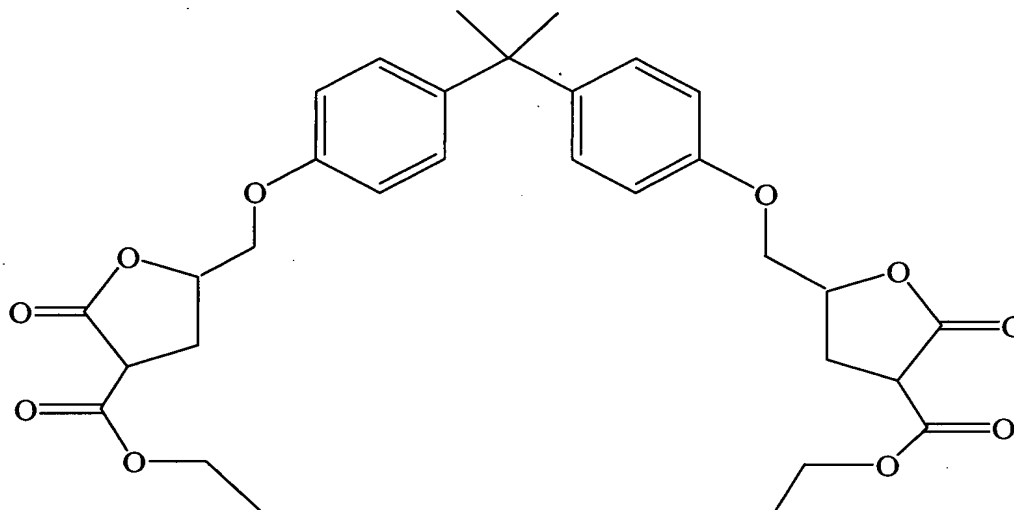
A vial was charged with 3 g of methyl phenylsulphonylacetate, 3 g of THF, and 1.62 g of sodium ethoxide. To this mixture was added 0.65 g of butyl glycidyl ether. The vial was placed under a pressure of 150 psig of nitrogen (to retard evaporation of the solvent) and heated at 100°C for four hours. The vial was cooled, depressurized, and the contents mixed with 1 ml of conc. hydrochloric acid and 2 ml of chloroform. The mixture was washed twice with 5 ml of water, separated, dried over magnesium sulfate, treated with charcoal,

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filtered, and the solvent removed on the rotary evaporator to give a syrup. IR (neat) 1778.92 and 1743.69 cm^{-1} (cis and trans lactone isomers). ^1H NMR (CDCl_3) 4.6 and 4.75 ppm (both m, cis and trans isomers of 5-H lactone ring).

EXAMPLE 4

5 Synthesis of (1-Methylethylidene)bis(4,1-phenyleneoxymethylene)-bis[5-(3-carboethoxyfuran-2-one)]



10 A pressure vessel was charged with 5.05 g of diethyl malonate, 9.5 g of ethanol, and 10.5 g of sodium ethoxide. To this mixture was added 5.1 g of bisphenol-A diglycidyl ether. The bomb was sealed, pressured with 150 psig with nitrogen and then heated to 100°C for two hours. The bomb was cooled, depressurized, and the product neutralized with conc. hydrochloric acid. The
15 product was taken up in chloroform, washed with water, dried over magnesium sulfate, filtered, and the solvent removed to give 6.6 g (80% yield) of resinous product. By proton NMR, all the epoxy groups had been converted to product. IR (neat) 1780.88 (lactone carbonyl), 1735.92 cm^{-1} . ^1H NMR (CDCl_3) 4.8 and 4.9 ppm (both m, cis and trans isomers of 5-H lactone ring).

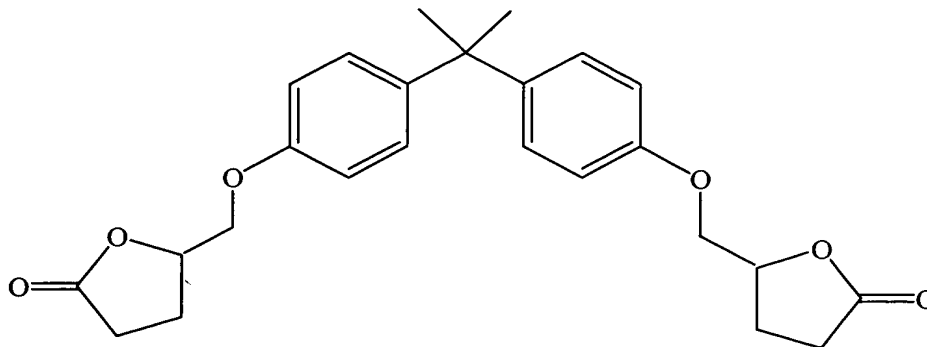
EXAMPLE 5

20 Synthesis of (1-Methylethylidene)bis(4,1-phenyleneoxymethylene)-bis[5-(3-carbomethoxyfuran-2-one)]

A similar reaction to that found in Example 4, using dimethyl malonate in place of diethyl malonate, gave the corresponding carbomethoxy derivative. Use
25 of higher temperature for this reaction (100°C rather than refluxing methanol) resulted in a distinctly higher yield (95% vs. 45%).

EXAMPLE 6

(1-Methylethylidene)bis(4,1-phenyleneoxymethylene)bis[5-(furan-2-one)]



5

A 100 ml round bottomed flask was charged with 0.7 g of anhydrous magnesium chloride, 32 ml of dimethyl acetamide and 6 drops of water. To the flask was added 4.4 g of (1-methylethylidene)bis(4,1-

10

phenyleneoxymethylene)bis[5-(3-carboethoxyfuran-2-one)] as synthesized in Example 4 above. After refluxing the mixture for 40 min., IR spectra revealed that the lactone carbonyl peak at 1780 cm^{-1} remained and the ester carbonyl peak at 1735 cm^{-1} was absent. Subsequently, it was found that heating the starting material in a vial under nitrogen pressure at 200 psig at a temperature of 150°C using hydrochloric acid or tosic acid was also effective for complete

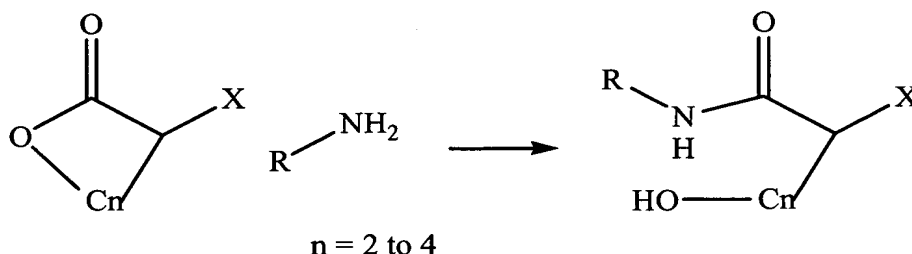
15

decarboethoxylation.

Aminolysis of Gamma-Butyrolactones

The aminolysis of gamma-butyrolactones may be described as an amide forming reaction caused by the reaction of a primary amine with a lactone to give a hydroxyamide:

20



EXAMPLE 7

Aminolysis of Gamma-Butyrolactone

25

The aminolysis of the parent lactone, gamma-butyrolactone, was conducted in a sealed NMR tube that was held at room temperature ($21^{\circ}\text{C} \pm 1^{\circ}\text{C}$) during the course of the experiment. The integrated intensity of two peaks was monitored. The peaks corresponded to the methylene group adjacent to the

ester ring oxygen of the lactone (triplet located at 4.3 ppm) and the methylene group adjacent to the nitrogen in butyl amine (triplet located at 2.5 ppm). The ratio of ester/amine was computed and is shown as % concentration of lactone in the table below.

5

EXAMPLE 8

Aminolysis of 3-cyano-5-phenoxyethyl-gamma-butyrolactone

A solution of 3-cyano-5-phenoxyethyl-gamma-butyrolactone (as prepared in Example 1) was prepared by weighing into a NMR tube 0.0893 g (0.0004375 mol) of 3-cyano-5-phenoxyethyl-gamma-butyrolactone and 10 0.0147 g of durene dissolved in 0.589 g of DMF-d₇. Then 0.043 ml (0.0004375 mol) of N-butylamine was added. The tube was sealed and the ¹H NMR spectrum recorded at various times. The integrated intensity of the triplet due to the methylene group adjacent to the nitrogen atom of butylamine at 2.58 ppm (here designated "a") and the integrated intensity of the triplet due to the 15 methylene group adjacent to the amido nitrogen at 3.18 ppm (here designated "b") were used to calculate the relative concentration of butylamine in the mixture; the relative decrease in the concentration of the amine at a given time was calculated as a/(a+b). The time at which the amine and amide were equal in concentration was estimated to be 5.0 min. When compared to the aminolysis rate of the parent 20 unsubstituted lactone, the relative half-life must be adjusted by dividing this time by a factor of 4 to compare rates since the reaction is approximately second order and the concentration was 1/2 of the concentration of the control. The half life was found to be 1.25 min.

EXAMPLE 9

Aminolysis of 5,5'-[1,4-butylenebis(oxymethylene)]-bis[ethyl(tetrahydro--2-oxo)-3-furancarboxylate]

A solution of 5,5'-[1,4-butylenebis(oxymethylene)]-bis[ethyl(tetrahydro--2-oxo)-3-furancarboxylate (as prepared in Example 2) was prepared by weighing into a NMR tube 0.1883 g (0.0004375 mol) of 5,5'-[1,4- 30 butylenebis(oxymethylene)]-bis[ethyl(tetrahydro--2-oxo)-3-furancarboxylate and 0.0291 g of durene dissolved in 0.441 g of DMF-d₇. Then 0.086 ml (0.000875 mol) of N-butylamine was added. The tube was sealed and the ¹H NMR spectrum recorded at various times. The integrated intensity of the triplet due to the methylene group adjacent to the nitrogen atom of butylamine at 2.58 ppm (here designated "a") and the integrated intensity of the triplet due to the 35 methylene group adjacent to the amido nitrogen at 3.13 ppm (here designated "b") were used to calculate the relative concentration of butylamine in the mixture; the

relative decrease in the concentration of the amine at a given time was calculated as $a/(a+b)$. The half life was found to be 88 min.

EXAMPLE 10

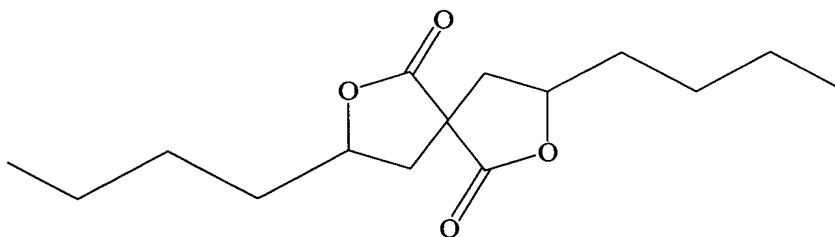
Aminolysis of 3-benzenesulfonyl-5-methyleneoxybutyl-butyrolactone

- 5 A solution of 3-benzenesulfonyl-5-methyleneoxybutyl-butyrolactone was prepared by weighing into a vial 0.1367 g (0.0004375 mol) of 3-benzenesulfonyl-5-methyleneoxybutyl-butyrolactone and 0.0145 g (0.000109 mol) of durene in 0.5418 g of CDCl_3 . The solution was transferred to an NMR tube. The tube was cooled in an ice bath to 5°C and then 0.043 ml (0.0004375 mol) of N-butylamine
- 10 was added. The tube was sealed and the ^1H NMR spectrum recorded at various times. The integrated intensity of the triplet due to the methylene group adjacent to the nitrogen atom of butylamine at 2.58 ppm (here designated "a") and the integrated intensity of the two multiplets at 4.6 and 4.75 ppm (here designated "b") were used to calculate the relative concentration of butylamine in the
- 15 mixture; the relative decrease in the concentration of the amine at a given time was calculated as $a/(a+b)$. The reaction of the lactone having the sulfonyl group was so rapid that the half life $\{a/(a+b) = 0.5\}$ had to be estimated from only a few data points. The time at which the amine and amide were equal in concentration was estimated to be 1.0 min. When compared to the aminolysis rate of the parent
- 20 unsubstituted lactone, the relative half-life must be adjusted by dividing this time by a factor of 4 to compare rates since the reaction is approximately second order and the concentration was 1/2 of the concentration of the control.

EXAMPLE 11

Aminolysis of 3,8-Dibutyl-2,7-dioxaspiro[4.4]nonane-1,6-dione

25



- 3,8-Dibutyl-2,7-dioxaspiro[4.4]nonane-1,6-dione was prepared according to W. E. Fristad and S. S. Hershberger, J. Org. Chem., 1985, 50(7), 1026-1031.
- 30 Aminolysis of this lactone was followed by IR spectroscopy. The spiro lactone reacted rapidly in one ring and more slowly in the second ring.

Relative Aminolysis Rates of Unsubstituted and
Substituted Gamma-Butyrolactones

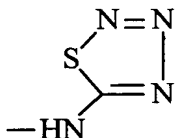
- 5 Using the half-life for butyrolactone determined above (9926 min) and the aminolysis data given in Table 2 below, the relative aminolysis rates for the substituted gamma-butyrolactones can be calculated as described above. These rates are expressed as $\log(k/k_0)$, and are plotted versus the F value for the functional group at 21°C as given in C. Hansch, et al., Chem. Rev., **1991**, *91*, pp. 165-195. This plot is shown in Figure 1.

Table 1

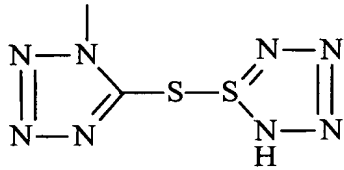
	Substituent	F ^b
1	BF ₂	0.26
2	Br	0.45
3	GeBr ₃	0.61
4	SiBr ₃	0.44
5	Cl	0.42
6	HgCl	0.33
7	SO ₂ Cl	1.16
8	SCl	0.42
9	ICl ₂	1.03
10	P(O)Cl ₂	0.70
11	PCl ₂	0.50
12	P(S)Cl ₂	0.63
13	GeCl ₃	0.65
14	SiCl ₃	0.44
15	F	0.45
16	HgF	0.35
17	SOF	0.67
18	SO ₂ F	0.72
19	IF ₂	0.82
20	POF ₂	0.74
21	PF ₂	0.44
22	GeF ₃	0.76
23	SF ₃	0.63
24	SiF ₃	0.47
25	IF ₄	0.98
26	PF ₄	0.54
27	SF ₅	0.56
28	I	0.42
29	IO	0.55
30	IO ₂	0.61
31	NO	0.49
32	NO ₂	0.65
33	ONO ₂	0.48
34	N≡N ⁺	1.58
35	N≡N ⁺ (BF ₄) ⁻	1.48

	Substituent	F ^b
36	NNO ₂ ⁻	0.20
37	N ₃	0.48
38	O ⁻	-0.26
39	SO ₂ ⁻	0.03
40	SO ₃ ⁻	0.29
41	S ⁻	0.03
42	AsO ₃ H ⁻	0.04
43	H	0.03
44	NHNO ₂	0.99
45	OH	0.33
46	S(O)OH	0.01
47	PO ₃ H ⁻	0.19
48	OPO ₃ H ⁻	0.41
49	SH	0.30
50	B(OH) ₂	-0.03
51	NH ₂	0.08
52	NHOH	0.11
53	SO ₂ NH ₂	0.49
54	PO(OH) ₂	0.34
55	PH ₂	0.09
56	B(OH) ₃ ⁻	-0.42
57	GeH ₃	0.03
58	NH ₃	0.92
59	NHNH ₂	0.22
60	SiH ₃	0.06
61	CBr ₃	0.28
62	CClF ₂	0.40
63	5-chloro-1-tetrazolyl	0.58
64	CoCl	0.46
65	N=CCl ₂	0.26
66	CCl ₃	0.38
67	OCCl ₃	0.46
68	COF	0.48
69	OCF ₂ O	0.36

	Substituent	F ^b
70	CF ₃	0.38
71	HgCF ₃	0.29
72	HgSCF ₃	0.38
73	I=NSO ₂ CF ₃	1.20
74	N=NCF ₃	0.50
75	OCF ₃	0.39
76	SOCF ₃	0.58
77	SeOCF ₃	0.76
78	SO ₂ CF ₃	0.74
79	SeO ₂ CF ₃	0.97
80	OSO ₂ CF ₃	0.56
81	SCF ₃	0.36
82	SeCF ₃	0.43
83	HgCN	0.27
84	CN	0.51
85	NC	0.47
86	CN(BBr ₃)	0.64
87	CN(BCl ₃)	0.93
88	CN(BF ₃)	0.71
89	N=C=O	0.31
90	OCN	0.69
91	SO ₂ CN	0.97
92	N=C=S	0.51
93	SCN	0.49
94	SeCN	0.57
95	N=NCN	0.56
96	N(O)=NCN	0.70
97	C(NO ₂) ₃	0.65
98	5-azido-1-tetrazolyl	0.53
99	CO ₂ ⁻	-0.10
100	CHBr ₂	0.31
101	CHCl ₂	0.31
102	OCHCl ₂	0.43
103	CHF ₂	0.29

	Substituent	F ^b
104	OCHF ₂	0.37
105	SOCHF ₂	0.51
106	SO ₂ CHF ₂	0.67
107	SCHF ₂	0.32
108	S(O)(=NH)CF ₃	0.64
109	NHSO ₂ CF ₃	0.45
110	CHI ₂	0.27
111	NHCN	0.28
112	1-(1H)-tetrazolyl	0.52
113	5-(1H)-tetrazolyl	0.65
114	5-hydroxy-1-tetrazolyl	0.41
115	5-mercapto-1-tetrazolyl	0.44
116		0.35
117	CHO	0.33
118	COOH	0.34
119	CH ₂ Br	0.14
120	CH ₂ Cl	0.13
121	OCH ₂ Cl	0.33
122	CH ₂ F	0.15
123	OCH ₂ F	0.29
124	SCH ₂ F	0.25
125	CH ₂ I	0.12
126	NHCHO	0.28
127	CONH ₂	0.26
128	CSNH ₂	0.24
129	CH=NOH-t	0.28
130	3,4-N=CHNH-	-0.10
131	N(O)=NCONH ₂	0.56
132	OCH ₂ O	-0.11
133	Me	0.01
134	CH ₂ SO ₂ R	0.16
135	SiMeCl ₂	0.29

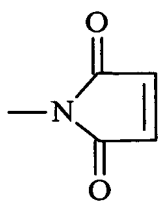
	Substituent	F ^b
136	SiMeF ₂	0.32
137	HgMe	0.55
138	NHCH ₂ SO ₃ ⁻	0.12
139	NHCONH ₂	0.09
140	N(Me)NO ₂	0.43
141	NHCSNH ₂	0.26
142	OMe	0.29
143	CH ₂ OH	0.03
144	SOMe	0.52
145	S(OMe)	0.24
146	OS(=O)CH ₃	0.43
147	S(O)OMe	0.47
148	SO ₂ Me	0.53
149	SSO ₂ Me	0.38
150	OSO ₂ Me	0.40
151	SMe	0.23
152	SSMe	0.27
153	SeMe	0.16
154	NHMe	0.03
155	CH ₂ NH ₂	0.04
156	NHSO ₂ Me	0.28
157	CH ₂ NH ₃ ⁺	0.59
158	N(COF) ₂	0.57
159	HgOCOCF ₃	0.48
160	COCF ₃	0.54
161	SCOCF ₃	0.48
162	OCOCF ₃	0.58
163	N(CF ₃)C=O(F)	0.49
164	CF ₂ OCF ₂ ⁻	0.77
165	CF ₂ CF ₃	0.44
166	OCF ₂ CF ₃	0.55
167	SO ₂ CF ₂ CF ₃	0.81
168	SCF ₂ CF ₃	0.42
169	N(CF ₃) ₂	0.35
170	S(CF ₃)=NSO ₂ CF ₃	1.07

	Substituent	F ^b
171	SO(CF ₃)-NSO ₂ CF ₃	1.09
172	N(SO ₂ CF ₃) ₂	0.50
173	P(CF ₃) ₂	0.55
174	P(CN) ₂	0.75
175	C≡CH	0.22
176	OCF ₂ CHCFCI	0.38
177	NHCOCF ₃	0.38
178	CH=NSO ₂ CF ₃	0.63
179	OCF ₂ CHF ₂	0.38
180	SCF ₂ CHF ₂	0.35
181		0.60
182	SC≡CH	0.30
183	SCH=CHCl	0.34
184	SeCH=CHCl	0.30
185	CH ₂ CF ₃	0.15
186	CH ₂ SOCF ₃	0.27
187	CH ₂ SO ₂ CF ₃	0.29
188	CH ₂ SCF ₃	0.13
189	CH ₂ CN	0.17
190	CH=CHNO ₂ -t	0.35
191	CH ₂ CO ₂ ⁻	0.19
192	CH ₂ SCN	0.14
193	CH=CH ₂	0.13
194	NHCOCH ₂ Cl	0.27
195	N(Me)SO ₂ CF ₃	0.46
196	HgOCOCH ₃	0.39
197	C(Me)(NO ₂) ₂	0.50
198	oxiranyl	0.09
199	OCH=CH ₂	0.34
200	COMe	0.33
201	SCOMe	0.37

	Substituent	F ^b
202	OCOMe	0.42
203	COOMe	0.34
204	2-thiacyclopropyl	0.08
205	SCH=CH ₂	0.29
206	SeCH=CH ₂	0.29
207	1-aziridinyI	0.03
208	2-aziridinyI	-0.01
209	N-methyl-3-oxaziridinyI	0.10
210	NHCOOMe	0.07
211	NHCOMe	0.31
212	CONHMe	0.35
213	CH=NOMe	0.40
214	CH ₂ CONH ₂	0.08
215	NHCSMe	0.30
216	CSNHMe	0.29
217	CH=NNHSCNH ₂	0.46
218	OCH ₂ CH ₂ O ⁻	-0.08
219	Et	0.00
220	CH=NNHCONHNH ₂	0.26
221	OCH ₂ CH ₃	0.26
222	CH(OH)Me	0.16
223	CH ₂ OMe	0.13
224	SO ₂ Et	0.59
225	SEt	0.26
226	P(Cl)NMe ₂	0.31
227	CH ₂ SC(NH ₂) ₂ ⁺	0.14
228	SiClMe ₂	0.16
229	SiFMe ₂	0.12
230	NHEt	-0.04
231	N(Me) ₂	0.15
232	N(Me)SO ₂ Me	0.21
233	SO ₂ NMe ₂	0.44
234	N(SO ₂ Me) ₂	0.45
235	SN(Me) ₂	0.15
236	N=NNMe ₂	-0.02

	Substituent	F ^b
237	N(Me)N ⁺ =(Me)N-	1.10
238	P(O)Me ₂	0.40
239	PO(OMe) ₂	0.37
240	PMe ₂	0.05
241	S ⁺ Me ₂	0.98
242	S ⁺ (Me) ₂ tosyl	1.04
243	CH ₂ CH ₂ NH ₃ ⁺	0.27
244	SiH(Me) ₂	0.03
245	1-(1,7(BH) ₁₀ -C ₂ H)	0.23
246	2-(1,7(BH) ₁₀ -C ₂ H)	0.16
247	4-(1,7(BH) ₁₀ -C ₂ H)	0.00
248	1-(1,2(BH) ₁₀ -C ₂ H)	0.50
249	3-(1,2(BH) ₁₀ -C ₂ H)	0.22
250	C≡CCF ₃	0.37
251	CF=CF CF ₃ -t	0.36
252	N=C(CF ₃) ₂	0.32
253	CF ₂ CF ₂ CF ₃	0.42
254	CF(CF ₃) ₂	0.31
255	SO ₂ CF ₂ CF ₂ CF ₃	0.81
256	SO ₂ CF(CF ₃) ₂	0.80
257	SCF ₂ CF ₂ CF ₃	0.43
258	SCF(CF ₃) ₂	0.46
259	TeCF ₂ CF ₂ CF ₃	0.45
260	C(OH)(CF ₃) ₂	0.29
261	CH(SCF ₃) ₂	0.43
262	CH(CN) ₂	0.52
263	CH=CHCF ₃ -c	0.18
264	CH=CHCF ₃ -t	0.24
265	CH=CHSO ₂ CF ₃	0.22
266	CH=CHCN	0.28
267	C≡CMe	0.29
268	N(Me)COCF ₃	0.41
269	CH=CHCHO	0.29
270	cyclopropyl	0.02
271	C(Me)=CH ₂	0.13

	Substituent	F ^b
272	CH=CHMe- <i>t</i>	0.09
273	CH ₂ CH=CH ₂	-0.06
274	C(Et)(NO ₂) ₂	0.51
275	OCH ₂ CH=CH ₂	0.25
276	COEt	0.34
277	COOEt	0.34
278	CH ₂ OCOMe	0.07
279	CH ₂ CH ₂ COOH	0.02
280	SCH ₂ CH=CH ₂	0.23
281	SeCH ₂ CH=CH ₂	0.26
282	CH ₂ CH ₂ CH ₂ -	-0.20
283	N(Me)COMe	0.34
284	CH ₂ NHCOMe	0.12
285	NHCOOEt	0.23
286	C(NO ₂)Me ₂	0.19
287	OCH ₂ CH ₂ CH ₂ O-	0.03
288	isopropyl	0.04
289	CH ₂ CH ₂ CH ₃	0.01
290	N ⁺ (Me)=CHN(Me)-	1.05
291	NHCONHEt	0.19
292	NHCSNHEt	0.40
293	OCHMe ₂	0.34
294	OCH ₂ CH ₂ CH ₃	0.26
295	CH ₂ CH(OH)Me	-0.06
296	C(OOH)Me ₂	0.17
297	SCHMe ₂	0.30
298	CH ₂ NMe ₂	0.03
299	GeMe ₃	0.03
300	N ⁺ (Me) ₃	0.86
301	CH ₂ NH ⁺ (Me) ₂	0.39
302	Si(Me) ₂ OMe	0.09
303	OSiMe ₃	0.31
304	SiMe(OMe) ₂	0.05
305	Si(OMe) ₃	0.10
306	P ⁺ Me ₃	0.71

	Substituent	F ^b
307	SiMe ₃	0.01
308	SnMe ₃	0.03
309	1-(1,2-(BH) ₁₀ -C ₂ Me)	0.43
310	CH ₂ -1-(1,7-(BH) ₁₀ -C ₂ H)	0.03
311	CH ₂ -1-(1,2-(BH) ₁₀ -C ₂ H)	0.14
312	1-(1,2-(BH) ₁₀ -C ₃ H ₃ HgCH ₃)	0.82
313	2-(hydroxymethyl)carboran-1-yl	0.34
314	I(OCOCF ₃) ₂	1.18
315	cyclo-C ₄ F ₇	0.45
316	COCF ₂ CF ₂ CF ₃	0.55
317	C(CF ₃) ₃	0.53
318	(CF ₂) ₃ CF ₃	0.44
319	SO ₂ C(CF ₃) ₃	0.84
320	SC(CF ₃) ₃	0.47
321	C(SCF ₃) ₃	0.49
322	SeC(CF ₃) ₃	0.46
323	C(CN) ₃	0.92
324	cyclo-1-(OH)C ₄ F ₆	0.36
325	CH=C(CN) ₂	0.57
326	2-(5-bromofuryl)	0.23
327		0.36
328	3-chloro=1-pyrroline-2,5-dione	0.47
329	3-pyridazinyl	0.21
330	3,4-CH=CHCH-CH-	0.07
331	C(Me)(CN) ₂	0.59
332	4-pyrimidinyl	0.18
333	2-pyrimidinyl	0.13
334	5-pyrimidinyl	0.25
335	2-furyl	0.10
336	2-thienyl	0.13
337	3-thienyl	0.08

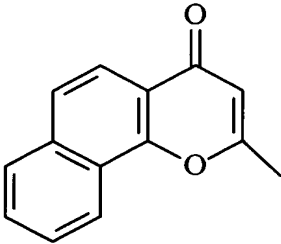
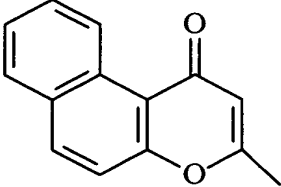
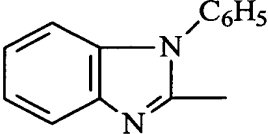
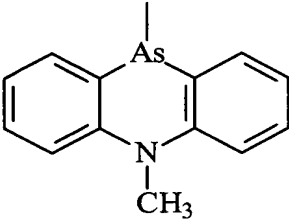
	Substituent	F ^b
338	2-selenienyl	0.10
339	2-tellurienyl	0.10
340	1-pyrryl	0.50
341	1-pyrroline-2,5-dione	0.36
342	CH=CHCOMe	0.31
343	I(OCOMe) ₂	0.80
344	N(COMe) ₂	0.36
345	cyclobutyl	0.02
346	COCHMe ₂	0.35
347	(CH ₂) ₄	-0.40
348	NHCOCH(Me) ₂	0.21
349	C(Me) ₃	-0.02
350	CH(Me)Et	-0.02
351	CH ₂ CH(Me) ₂	-0.01
352	(CH ₂) ₃ CH ₃	-0.01
353	O(CH ₂) ₃ CH ₃	0.29
354	CH ₂ C(OH)Me ₂	-0.11
355	C(OMe) ₃	0.01
356	AsEt ₂	0.32
357	As(O)Et ₂	0.60
358	As(S)Et ₂	0.54
359	NH(CH ₂) ₃ CH ₃	-0.21
360	N(Et) ₂	0.01
361	PO(Et) ₂	0.33
362	N=NPO(OEt) ₂	0.05
363	PO(OEt) ₂	0.52
364	P(Et) ₂	0.11
365	P(S)Et ₂	0.36
366	CH ₂ N(Me) ₃ ⁺	0.38
367	CH ₂ CH ₂ NH(Me) ₂ ⁺	0.29
368	CH ₂ OSi(CH ₃) ₃	0.00
369	CH ₂ Si(Me) ₃	-0.09
370	PO(N(Me) ₂) ₂	0.27
371	P(N(Me) ₂) ₂	0.17
372	2-(methylcarbonyl)carboran-1-yl	0.31

	Substituent	F ^b
373	2-[(carbonyloxy)methyl]carboran-1-yl	0.66
374	CH ₂ -1-(1,2-(BH) ₁₀ -C ₂ Me)	0.12
375	C(CN)=C(CN) ₂	0.65
376	2-(5-cyanofuryl)	0.32
377	2-(5-formylfuryl)	0.34
378	2-pyridyl	0.40
379	3-pyridyl	0.24
380	4-pyridyl	0.21
381	2-(4,6-dimethyl-s-triazinyl)	0.21
382	1-cyclopentenyl	-0.03
383	CH=CHCOOEt	0.27
384	cyclopentyl	0.02
385	COC(Me) ₃	0.26
386	NHCO ₂ (CH ₂) ₃ CH ₃	0.13
387	C(Et)(Me) ₂	0.03
388	CH ₂ C(Me) ₃	0.03
389	(CH ₂) ₄ CH ₃	-0.01
390	O(CH ₂) ₄ CH ₃	0.29
391	CH ₂ PO(OEt) ₂	0.17
392	CH ₂ CH ₂ N(Me) ₃ ⁺	0.19
393	CH ₂ CH ₂ Si(Me) ₃	-0.11
394	Si(Me) ₂ OSi(Me) ₃	0.04
395	C ₆ Cl ₅	0.27
396	C ₆ F ₅	0.27
397	P(O)(C ₃ F ₇) ₂	0.84
398	OP(O)(C ₃ F ₇) ₂	0.67
399	NHP(O)(C ₃ F ₇) ₂	0.33
400	CH ₂ Co(CN) ₅ ⁻³	-0.39
401	CH ₂ Mn(CO) ₅	0.02
402	C ₆ H ₂ -2,4,6-(NO ₂) ₃	0.26
403	C ₆ H ₄ -3-Br	0.12
404	C ₆ H ₄ -4-Br	0.18
405	C ₆ H ₄ -3-Cl	0.19
406	C ₆ H ₄ -4-Cl	0.18
407	C ₆ H ₄ -3-F	0.19

	Substituent	F ^b
408	C ₆ H ₄ -4-F	0.17
409	OC ₆ H ₄ -4-F	-0.03
410	C ₆ H ₄ -3-I	0.18
411	C ₆ H ₄ -4-I	0.18
412	C ₆ H ₄ -3-NO ₂	0.23
413	C ₆ H ₄ -4-NO ₂	0.26
414	SC ₆ H ₄ -4-NO ₂	0.36
415	SOC ₆ H ₄ -4-NO ₂	0.55
416	2-benzotriazolyl	0.47
417	C ₆ H ₅	0.12
418	N(O)=NSO ₂ C ₆ H ₅	0.62
419	N=NC ₆ H ₅	0.30
420	OC ₆ H ₅	0.37
421	SOC ₆ H ₅	0.51
422	2-(5-acetylfuryl)	0.31
423	2-(6-methylpyronyl)	0.36
424	SO ₂ C ₆ H ₅	0.58
425	OSO ₂ C ₆ H ₅	0.37
426	SC ₆ H ₅	0.30
427	NHC ₆ H ₅	0.22
428	HNSO ₂ C ₆ H ₅	0.24
429	SO ₂ NHC ₆ H ₅	0.51
430	2-(5-ethylfuryl)	0.20
431	1-(2,5-dimethylpyrryl)	0.52
432	1-cyclohexenyl	-0.07
433	cyclohexyl	0.03
434	N(C ₃ H ₇) ₂	0.06
435	(CH ₂) ₄ NMe ₂	-0.01
436	PO(isopropyl) ₂	0.36
437	P(isopropyl) ₂	0.04
438	P(O)(OPr) ₂	0.33
439	Ge(Et) ₃	0.03
440	(CH ₂) ₃ N(Me) ₃ ⁺	0.12
441	Si(OEt) ₃	0.03
442	P(Et) ₃ ⁺	0.94

	Substituent	F ^b
443	Sn(Et) ₃	0.03
444	P(=NSO ₂ CF ₃)(C ₃ F ₇) ₂	1.11
445	Si(NMe ₂) ₃	0.00
446	2-benzoxazolyl	0.30
447	2-benzthiazolyl	0.27
448	COC ₆ H ₅	0.31
449	OCOC ₆ H ₅	0.26
450	COOC ₆ H ₅	0.34
451	N=CHC ₆ H ₅	0.14
452	CH=NC ₆ H ₅	0.33
453	NHCOC ₆ H ₅	0.13
454	CONHC ₆ H ₅	0.17
455	C ₆ H ₅ -4-Me	0.12
456	CH ₂ C ₆ H ₅	-0.04
457	N=NC ₆ H ₃ -5-Me-2-OH	0.26
458	C ₆ H ₄ -4-OMe	0.13
459	CH(OH)C ₆ H ₅	0.05
460	CH ₂ OC ₆ H ₅	0.08
461	CH ₂ SO ₂ C ₆ H ₅	0.17
462	C(Et) ₃	0.02
463	(CH ₂) ₆ CH ₃	0.00
464	SiMe(OSi(Me) ₃) ₂	0.01
465	CF ₂ CF ₂ C ₆ H ₄ -4-F	0.32
466	C≡CC ₆ H ₅	0.15
467	CH=NCOC ₆ H ₅	0.34
468	CH=CHC ₆ H ₅	0.10
469	CH ₂ Fe(CO) ₂ (χ-C ₅ H ₅)	-0.11
470	CH=NNHCOC ₆ H ₅	0.34
471	N-CHC ₆ H ₄ -4-OMe	0.15
472	NHCOC ₆ H ₄ -4-OMe	0.17
473	SCH=NSO ₂ C ₆ H ₄ -4-Me	0.61
474	C ₆ H ₄ -4-Et	0.13
475	CH ₂ CH ₂ C ₆ H ₅	-0.01
476	N=C(Me)NHC ₆ H ₅	0.38
477	Si(C ₆ H ₅)(Me) ₂	0.06

	Substituent	F ^b
478	S(Me)=NSO ₂ C ₆ H ₄ -4-Me	0.61
479	2,4,6-trimethylpyridinium	0.61
480	PO(CMe ₃) ₂	0.28
481	PO(C ₄ H ₉) ₂	0.30
482	PO(OC ₄ H ₉) ₂	0.35
483	P(CMe ₃) ₂	-0.01
484	C ₆ H ₅ Cr(CO) ₃	0.36
485	2-benzo-4-thiopyronyl	0.34
486	2-(benzothiopyronyl)	0.48
487	2-(benzo-1,4-pyronyl)	0.41
488	CH=CHCOC ₆ H ₄ -4-NO ₂	0.21
489	CH ₂ Mo(CO) ₃ (C ₅ H ₅)	-0.07
490	CH=CHCOC ₆ H ₅	0.25
491	C ₆ H ₄ -4-CHMe ₂	0.13
492	Si(OSiMe ₃) ₃	-0.08
493	ferrocenyl	-0.09
494	ferricenium ⁺	0.30
495	ferrocenonium ⁺	-0.01
496	C ₆ H ₄ -4-CMe ₃	0.12
497	1-adamantyl	-0.07
498	1-dibenzarsenyl	0.23
499	1-dibenzoarsoxyl	0.22
500	1-dibenzoarsazinyl	0.18
501	As(C ₆ H ₅) ₂	0.04
502	AsO(C ₆ H ₅) ₂	0.49
503	P(C ₆ H ₅) ₂ (BCl ₃)	0.62
504	N(C ₆ H ₅) ₂	0.12
505	PO(C ₆ H ₅) ₂	0.32
506	P(C ₆ H ₅) ₂	0.10
507	PS(C ₆ H ₅) ₂	0.22
508	P(N(C ₃ H ₇) ₂)C ₆ H ₄ -3-F	0.20

	Substituent	F ^b
509		0.37
510		0.38
511		0.17
512	CH(C ₆ H ₅) ₂	0.01
513		0.16
514	PO(C ₆ H ₅)C ₆ H ₄ -4-Me	0.09
515	CH ₂ PO(C ₆ H ₅) ₂	0.21
516	PS(C ₆ H ₅)C ₆ H ₄ -4-Me	0.03
517	P ⁺ (Me)(C ₆ H ₅) ₂	1.04
518	Si(Me)(C ₆ H ₅) ₂	0.11
519	COOCH(C ₆ H ₅) ₂	0.28
520	PO(C ₆ H ₄ -4-Me) ₂	0.14
521	PS(C ₆ H ₄ -4-Me) ₂	0.20
522	P ⁺ (Me)(C ₆ H ₅)(C ₆ H ₄ -4-Me)	1.02
523	P ⁺ (Me)(C ₆ H ₄ -4-Me) ₂	1.04
524	Ge(C ₆ H ₅) ₃	0.07
525	2-methyl-4,6-diphenylpyridinium	0.61

	Substituent	F ^b
526	N=P(C ₆ H ₅) ₃	-0.10
527	Si(C ₆ H ₅) ₃	-0.04
528	Sn(C ₆ H ₅) ₃	(0.62)
529	C(C ₆ H ₅) ₃	0.01
530	2,4,6-triphenylpyridinium	0.35

Table 2:
Kinetic Values and Reaction Rates for Unsubstituted
and Substituted Gamma-Butyrolactones

Ex. No.	Func. Group	F Value	Equiv. Lactone and BuNH ₂	Obs. Crossover time (min.)	Kinetic Correction Factor	Corrected t _{1/2} (min)	Log (k/k ₀)
1	CN	0.51	0.000437	5	¼	1.25	3.90
3	SO ₂ phenyl	0.58	0.000437	1	¼	0.25	4.60
Parent	H	0.03	0.000875	9926	1	9926	0
2	CO ₂ Et	0.34	0.000875	88	1	88	2.05